Measurements for EIC at JLab

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The physics program of an EIC

**Map the spin and spatial structure of sea quarks and gluons in nucleons**
- Sea quark and gluon polarization
- Transverse spatial distributions
- Orbital motion of sea quarks / gluons
- Parton correlations: beyond one-body densities

**Discover the collective effects of gluons in nuclei**
- Color transparency: small-size configurations
- Nuclear gluons: EMC effect, shadowing
- Strong color fields: unitarity limit, saturation
- Fluctuations: diffraction

**Understand the emergence of hadronic matter from color charge**
- Materialization of color: fragmentation, hadron breakup, color correlations
- Parton propagation in matter: radiation, energy loss

*Note that already EIC Stage I will address all major areas!*
The EIC project is pursued jointly by BNL and JLab, and both labs work towards implementing a common set of goals

- Polarized electron, nucleon, and light ion beams
  - Electron and nucleon polarization > 70%
  - Transverse polarization at least for nucleons
- Ions from hydrogen to A > 200
- Luminosity reaching $10^{34}$ cm$^{-2}$s$^{-1}$
- Stage I energy: $\sqrt{s} = 20 – 70$ GeV (variable)
- Stage II energy: $\sqrt{s}$ up to about 150 GeV

From base EIC requirements in the INT report
<table>
<thead>
<tr>
<th>eRHIC @ BNL</th>
<th>MEIC / ELIC @ JLab</th>
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</thead>
<tbody>
<tr>
<td><strong>Stage I</strong></td>
<td><strong>Stage II</strong></td>
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<tr>
<td>$\sqrt{s} = 34 - 71$ GeV</td>
<td>$\sqrt{s} = \text{up to } \sim 180$ GeV</td>
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<tr>
<td>$E_e = 3 - 5 \ (10 \ ?) \ GeV$</td>
<td>$E_e = \text{up to } \sim 30$ GeV</td>
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<tr>
<td>$E_p = 100 - 255$ GeV</td>
<td>$E_p = \text{up to } 275$ GeV</td>
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<tr>
<td>$E_{Pb} = \text{up to } 100$ GeV/A</td>
<td>$E_{Pb} = \text{up to } \text{at least } 110$ GeV/A</td>
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</table>

$\sqrt{s} = 15 - 66$ GeV
$E_e = 3 - 11$ GeV
$E_p = 20 - 100$ GeV
$E_{Pb} = \text{up to } 40$ GeV/A

(ELIC)
The EIC at JLab – overview of accelerator

• Stage I (MEIC):
  – 3-11 GeV electrons on 20-100 GeV protons
  – About the same size as the 12 GeV CEBAF accelerator (1/3 of RHIC)

• Stage II (ELIC):
  – ~20 GeV electrons on 250+ GeV protons
MEIC – a figure-8 ring-ring collider

**The design makes possible:**

- Simultaneous use of both detectors
  - total beam-beam tune shift < 0.03
- Longitudinal and *transverse* polarization of light ions
  - protons, *deuterium*, $^3$He, ...
- Longitudinally polarized leptons
  - electrons and *positrons*
- Running fixed-target experiments in parallel with collider

**Reduced R&D challenges**
- Regular electron cooling
- Regular electron source
- No multi-pass ERL
MEIC – detectors

Space for 3 Interaction Points (IP)

- Main IPs located close to outgoing ion arc to reduce backgrounds

Primary detector (full acceptance)

- 7 m from IP to ion final-focus quads
- $\beta_y^* = 2$ cm, $\beta_x^* = 10-20$ cm, $\beta_{\text{max}} = 2.5$ km

Secondary detector (can be more limited)

- 4.5 m from IP to ion final-focus quads
  - Same as in BNL design

Special IP

- Space reserved for future needs
Full-acceptance detector – strategy

- **Central detector**, more detection space in ion direction as particles have higher momenta.

- Make use of the (50 mrad) crossing angle for ions!

- Detect particles with angles below ~0.5° beyond ion FFQs. Need up to 2 Tm dipole in addition to central solenoid.

- Detect particles with angles down to ~0.5° before ion FFQs.

- 50 mrad beam (crab) crossing angle

- 7 m

- 0 mrad

- 50 mrad

- Central detector

- Electron FFQs

- Ion dipole w/ detectors

- Ion FFQs

- Electrons

- Ions

- IP

- 2+3 m

- 2 m

- 2 m

- 60 mrad bend

- ultra forward hadron detection

- n, γ

- p

- p

- low-Q² electron detection

- large aperture electron quads

- central detector with endcaps

- small angle hadron detection

- ion quads

- small diameter electron quads

- 50 mrad (crab) crossing angle

- Central detector, more detection space in ion direction as particles have higher momenta.
Recoil baryon detection

• At high proton energies, recoil baryons are scattered at small angles
  – Lower proton energies give better small-\( t \) coverage and resolution in \(-t\)
  – Higher proton energies give better large-\( t \) acceptance at a given maximum ring energy
    • Lower maximum ring energy gives better acceptance at the actual running energy

• Good recoil baryon detection requires
  – Wide range of proton (deuteron) energies
  – Small beam size to reach low -\( t \) (relies on highly efficient cooling)
Spectator (and fragment) detection / tagging

Quasi-free neutron

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(Quasi)-free proton

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A. Accardi
Ultra-forward hadron detection – requirements

1. **Good acceptance for ion fragments** (rigidity different from beam)
   - Large downstream magnet apertures
   - Small downstream magnet gradients (realistic peak fields)

2. **Good acceptance for recoil baryons** (rigidity similar to beam)
   - Small beam size at second focus (to get close to the beam)
   - Large dispersion (to separate scattered particles from the beam)

3. **Good momentum- and angular resolution**
   - Large dispersion (e.g., 60 mrad bending dipole)
   - Long, instrumented magnet-free drift space

4. **Sufficient separation between beam lines (~1 m)**
To achieve all requirements, the accelerator team is designing the MEIC around the detector.
Small-angle hadron detection – summary

- Neutron detection in a 25 mrad cone down to zero degrees
- Excellent acceptance for all ion fragments

- Recoil baryon acceptance:
  - up to 99.5% of beam energy for all angles
  - down to 2-3 mrad for all momenta

- Momentum resolution $< 3 \times 10^{-4}$
  - limited by intrinsic beam momentum spread

- 100 GeV maximum ion energy allows using large-aperture magnets with achievable field strengths

![Diagram of hadron detection system]
Small-angle hadron acceptance – magnet fields

**Red**: Detection between the small upstream dipole and ion quadrupoles

**Blue**: Detection after the large downstream dipole
Small-angle hadron acceptance @ 9 T (100 GeV)

- **Red** and **Green**: Detection between upstream 2 Tm dipole and ion quadrupoles
- **Yellow**: Detection between ion quadrupoles and downstream 20 Tm dipole
- **Blue**: Detection after the 20 Tm downstream dipole

- Aperture of downstream dipole (blue) can be adjusted – shown shifted for illustration
- Angles shown are scattering angles at IP with respect to the ion beam direction
Neutron structure through spectator tagging

- In fixed-target experiments, scattering on *bound neutrons* is complicated
  - Fermi motion, nuclear effects
  - Low-momentum spectators

- Spectator tagging at the MEIC will allow flavor separation of spin and sea quark distributions
Spectator tagging with polarized deuterium

„If one could tag neutron, it typically leads to larger asymmetries“

- Longitudinal and transverse polarization for d, $^3$He, and other light ions
- Polarized neutrons are important for probing d-quarks through SIDIS
- Polarized neutrons are also important for exclusive reactions
Particle identification and central detector design

- Small differences in the desired range of $\pi/K$ separation has huge impact on detector layout
- What range in $p_{lab}$ (not $p_T$ or $k_T$) do you need?
- If you need 8-9 GeV, the detector may look like on the left (1 m radial space for PID)
- If 5-6 GeV is enough, the detector may look like this instead (0.1 m radial space for PID)

- TOF
- DIRC bar
- DIRC expansion volume
Summary

**EIC is the ultimate tool for studying sea quarks and gluons**

- The importance of Stage I cannot be overemphasized since this is the machine that is actually going to be built and operated for at least a decade before there is any chance for a Stage II to materialize.

**Common framework for JLab and BNL implementations**

- Global design parameters (energies, staging, etc) follow INT consensus

**MEIC at JLab offers many attractive capabilities**

- Wide range of proton (ion) energies
- Polarized deuterons and positrons
- Excellent detection of recoil baryons, spectators, and target fragments
Backup
Momentum resolution at the focal point

- Momentum resolution is given by the slope of the line
- Large deflections and long drift space allows precise tracking
  - Particles with deflections > 1 m will be detected closer to the large dipole
• Large crossing angle (50 mrad)
  – Moves spot of poor resolution along solenoid axis into the periphery
  – Minimizes shadow from electron FFQs

• Large-acceptance dipole further improves resolution in the few-degree range
Tracking: momentum resolution in a solenoid field

\[ \Delta p/p \sim \frac{\sigma p}{BR^2} \]

- Tracker (not magnet!) radius \( R \) is important at central rapidities
- Only solenoid field \( B \) matters at forward rapidities
- A 2 Tm dipole covering 3-5° can eliminate divergence at small angles
- A beam crossing angle moves the region of poor resolution away from the ion beam center line.
  - 2D problem!

particle momentum = 5 GeV/c
4 T ideal solenoid field
cylindrical tracker with 1.25 m radius (\( R_1 \))
Exclusive reactions with transverse “target“

DVCS on proton

\[ x = 10^{-3} \]

\[ \sin(\phi - \phi_s) \]

\[ A_{UT} \]

- DVCS on a transversely polarized target is sensitive to the GPD \( E \)
  - GPD \( H \) can be measured through the beam spin asymmetry

- Meson production is more selective: \( J/\Psi \) sensitive to corresponding gluon GPDs

- Colliders provide an excellent Figure-Of-Merit (FOM)
  - \( FOM = \text{Cross section} \times \text{Luminosity} \times \text{Acceptance} \times (\text{Polarization})^2 \times (\text{Target dilution})^2 \)

Model

\[ E'(x, \zeta, t) = \kappa(t) H'(x, \zeta, t) \]

Error bars shown only for \( \kappa^{sea} = +1.5 \)

F. Sabatie
Imaging in coordinate and momentum space

GPDs

2+1 D picture in **impact-parameter space**

- Accessed through *exclusive* processes
- Existing factorization theorems
- Ji sum rule for nucleon spin

TMDs

2+1 D picture in **momentum space**

- Accessed through *Semi-Inclusive* DIS
- Non-trivial factorization
- OAM through spin-orbit correlations?

QCDSF/UKQCD Coll., 2006

Anselmino et al., 2009

Lattice QCD

\[ F_{1T}(x) \text{ [Sivers function]} \]
TMDs and Orbital Angular Momentum (OAM)

- Do valence u and d quarks have opposite signs of their OAM?
- TMD data and Lattice calculations suggestive (despite different sum rules)
- What about sea quarks?
Helicity PDFs at an EIC

\[ g_1(x, Q^2) + \text{const}(x) \]

Q$^2 = 10$ GeV$^2$

\[ x\Delta g \]

5 x 250 starts here

5 x 100 starts here

M. Stratmann

W/ EIC data

Current data
Sea quark polarization

- Spin-Flavor Decomposition of the Light Quark Sea
  Needs intermediate $\sqrt{s} \sim 30$ (and good luminosity)

\[ \mathbf{p} = u \uparrow u \uparrow + u \uparrow d \uparrow + \ldots \]

Many models predict $\Delta u > 0$, $\Delta d < 0$
Target and current fragmentation in SIDIS

- Cannot separate intrinsic $k_T$ from soft FSI and fragmentation
- New insight from $p'_T$ of target fragments?
  - Origin of FSI? QCD radiation?
- EIC: current-target correlation measurements over wide range in $p_T$
Hadronization – parton propagation in matter

Accardi, Dupre

\[ \Delta p_T^2 \text{ vs. } Q^2 \]

- \( p_T \) broadening
- Fragmentation functions
- Heavy flavors: B, D mesons, J/\( \Psi \) ...
- Jets at \( s > 1000 \text{ GeV}^2 \)
  - "real" pQCD, IR safe
EIC Stage I

\[ s = E_{cm}^2 \ (GeV^2) \]

\[ s = E_e E_p = 4 \times 11 \times 100 = 4400 \text{ GeV}^2 \]

Medium-energy EIC (Stage I)

- \( s_{\text{max}} = 2 E_e M_p = 2 \times 11 \times 0.938 = 20 \text{ GeV}^2 \)
- \( s_{\text{max}} = 2 E_e M_p = 2 \times 160 \times 0.938 = 300 \text{ GeV}^2 \)

Fixed-target experiments

LHeC kinematic coverage is entirely complementary to a Stage I EIC
The EIC project will be pursued jointly by BNL and JLab in the Long Range Plan.